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Report on the Office of Naval Research Shallow-Water Acoustic Workshop, 1–3 October 1996

by

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As moderator of this workshop, I would like to thank a number of people for their efforts, cooperation, and goodwill for without them the Shallow-Water Acoustics Workshop would not have been possible. First, to Dr. Ellen Livingston for giving me the opportunity to serve as moderator; and for all her hard work in making it a success. Secondly, appreciation to the four group leaders for their wonderful jobs in leading the panels and ultimately providing the distilled results of their group's deliberations. They are: Drs. Paul Vidmar, Michael Buckingham, and William Siegmann, and Mr. Ed Chaika. I very gratefully acknowledge the co-sponsorship of this workshop by Dr. Bill Carey and DARPA. Bill's enthusiasm for shallow-water acoustics over the years has led to his making numerous contributions to the topic and his sponsorship of and participation in this workshop certainly is another significant contribution. Thanks to Ms. Bev Kuhn and the NRL staff people who took care of the paperwork, logistics, and other details involved in organizing this meeting. The workshop participants also deserve a big thank you -- being moderator of a meeting of an enthusiastic and talented group like the ocean acoustics community is very easy, indeed, as it is their minds and efforts that propelled the meeting. Finally, I'd like to thank my family for tolerating the sometimes extensive amount of traveling that the job of oceanographer entails.

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ABSTRACT

The results of an unclassified workshop on Shallow Water Acoustics, jointly sponsored by ONR and DARPA, are presented. The workshop was held on October 1-3, 1996 at the Naval Research Laboratory, Stennis Space Center, and included 83 participants specializing in ocean acoustics, geology and geophysics, physical oceanography, and other disciplines relevant to shallow water research. The goal of the workshop was to help determine the current status of and future directions for shallow water acoustics research. The report summarizes the deliberations and recommendations of the workshop, and includes detailed reports from the three working groups (bottom, water column, and modeling and signal processing) as well as from the workshop moderator (Dr. James Lynch, WHOI).

INTRODUCTION

On October 1-3, 1996 the Office of Naval Research, Code 321OA, and the DARPA ASW Shallow Water Program sponsored an unclassified workshop on Shallow-Water Acoustics at the Naval Research Laboratory at Stennis Space Center, Mississippi. Overall, the intent of this workshop was to have a variety of ocean acoustics investigators interact constructively in order to promote better vertical and horizontal integration among the basic research and the exploratory development research projects. The most significant objective of the workshop was to identify the strengths, needs, and goals of the present ONR Shallow-Water Acoustics program. Finally, the workshop provided an opportunity to discuss the Navy relevance of current research, especially identifying Navy exploratory development projects that are dependent on Shallow-Water Acoustics.

The workshop opened with several programmatic overview talks. These were followed by a full day of short project review and tutorial talks. On the second day, there were four consecutive open panel discussions on topics selected for their importance to current shallow-water acoustic research. These panels were: Bottom Acoustics (Group Leader, Paul Vidmar), Water Column Acoustics (Group Leader, Michael Buckingham), Acoustics Modeling /Signal Processing (Group Leader, William Siegmann), and Vertical and Horizontal Integration Issues (Group Leader, Ed Chaika). In the afternoon, the workshop participants broke into parallel working groups headed by the group leaders on the three technical research topics: Bottom Acoustics, Water Column Acoustics, and Acoustics Modeling/Signal Processing. On the final day of the workshop, the working groups reconvened to generate summary reports of their discussions which were presented at the concluding full session of the workshop. The written report which follows brings together and documents the results and recommendations from this workshop.

MODERATOR'S COMMENTARY ON THE OCT 1-3, 1996 ONR-DARPA SHALLOW WATER WORKSHOP

Jim Lynch, Moderator

Introduction

At my request, Drs. Ellen Livingston and Jeff Simmen accorded me the privilege of writing a small commentary on shallow water acoustics research, and in particular on the Oct. 1-3 Shallow Water Workshop held this autumn at NRL-SSC. Before embarking on this, however, I will make a very strong disclaimer that the statements and opinions contained in *this* section of the report are *strictly my own* and are *not* to be construed as representing either the opinion of the community or of the sponsors of the workshop.

I have written this section *not* because I have any claim to superior expertise in this field (I don't!), but rather because I think these comments may have some small added value in further focusing our results and adding a few more ideas for the future. If even one point I make is a good one that produces a positive result, it will have been worth the effort.

A Brief Revisionist History of Shallow Water Research (1977-1996)

I've now been in the field of underwater acoustic/ acoustical oceanography for 20 years, which gives me just enough of a time series of observations of the field of shallow water acoustics to say that there *is* such a thing as long term progress! When I first looked at shallow water acoustic propagation problems at ARL:UT some 20 years ago, there were decent 2-D ray and mode codes available. (PE was in its infancy and 3-D was a distant dream.) These codes were slow by modern standards, and most were range independent, but they worked. The characteristics of the bottom were known only in a very broad sense, and Hamilton's work was the roadmap for most uses. (His 1980 JASA paper is still highly regarded today, which indicates just how basic his contribution was.) The

water column was commonly regarded as something that could cavalierly be tossed off -- an XBT record in the general vicinity of interest was regarded as perfectly adequate information about the oceanographic field. By and large, "blue water" dominated people's attention anyway, so that the finer points of shallow water oceanography and geology were not first order worries.

In the decade of the 1980's, blue water still dominated the Navy's interest. However, shallow water was not entirely ignored, and research in the area proceeded at a goodly pace. Bottom acoustics was an important topic in the 80's, with much effort being put into measuring and computing what the effects of bottom and subbottom properties were on acoustic propagation. Inverse techniques for bottom properties, mainly linear, began to proliferate. Computer codes for propagation improved dramatically, with the PE and wavenumber integration techniques taking their places along with the standard ray and mode picture codes. Signal processing techniques, notably adaptive techniques and matched field processing (MFP), made substantial strides. Scattering from rough surfaces, particularly the water surface and the water bottom interface, was also explored extensively. The water column, however, remained largely ignored in the context of shallow water/ coastal acoustics.

The first half of the 1990's has also been a fruitful period for shallow water acoustics research. With the dissolution of the Soviet Union around 1990, and the tensions in the Middle East, the Navy's focus turned rather abruptly from "blue water" to "brown water," i.e. shallow water, as a top priority. In line with this, *two* shallow water workshops have been held by ONR this decade (1992 at WHOI and 1996 at NRL-SSC). The nineties have been the "era of the computer." The increase in computing power has made a great impact on modeling and analysis, whereas the decrease in computer size, the low power requirements, and the resistance to high g-forces that have enabled laptop computers to emerge have

made at-sea experimental observations at high bandwidths and over long durations practical. Computer codes have become sophisticated enough to handle much of the important propagation physics in 2-D slices, and 3-D and broadband codes now exist, though not all of them are as "user friendly" and efficient as one would desire them to be eventually. Thanks to these computer advances, bottom inversions using non-linear techniques such as simulated annealing and genetic algorithms have become possible, allowing the inversion of diverse data types for almost any geoacoustic or porous medium variable. Rapid bottom survey techniques are beginning to be developed, with chirp sonar being a prime example, but these also still have a long way to go.

Perhaps the biggest surprise in the 1990's has been the emergence of the water column as an important piece of the shallow water problem in the 25-2500 Hz range. The argument that the water column soundspeed fluctuations were small compared to the bottom property variations, and that in shallow water the downward refracting (or at least isovelocity) water column profile gave the bottom dominance more or less held sway until very recently. The fact that the low mode energy, which is the dominant energy propagated to longer ranges, travels mainly in the water column and thus is more strongly affected by its variability was largely overlooked. However, Zhou's 1991 Yellow Sea experiment paper in JASA started changing opinions about the water column's relative importance, and gave impetus to the current work on soliton scattering. The finding by the Barents Sea Polar Front group that the low modes were coupled far more strongly by a coastal front than by steep bottom bathymetry showed that these features, too, needed to be carefully considered. There have been numerous experiments recently which have focused on water column effects, and which have already shown them to be important determinants of shallow water acoustic propagation and scattering.

At this point, I am up to the present, so let me discontinue this brief "pseudo-historical" aside, and look at the present. I will do this by looking at the topics covered by the working groups.

Comments on the Working Group Topics

Before getting into the individual areas, I would first like to thank the panel and working group leaders for the wonderful jobs they have done. Ellen Livingston and I picked the leaders, Paul Vidmar, Mike Buckingham, Bill Siegmann, and Ed Chaika, because we knew that they all knew the fields they represented quite well and also were extremely dependable. Each group leader produced a fine report, and I thank them very much! The comments I'm adding here are, as I stated, just made in the hope of adding a little more value to their already excellent reports.

Bottom Acoustics

In doing *any* shallow water acoustics experiment, the bottom properties need to be determined to some extent for analysis purposes. However, it can be confidently stated that the bottom properties are the hardest quantities to obtain experimentally. *Rapid* survey techniques for getting at bottom properties are relatively rare (chirp sonar and shots/ airguns with sonobuoy receivers are two common ones I am aware of). More needs to be done, I feel, to make some of the other experimental techniques which have been developed for research into survey techniques, e.g. Hankel transform techniques, impact drop probes, etc., into common survey instruments. (As I type this in Hawaii, I have just learned from Bob Stoll that Sippecan *is* developing a commercial drop probe with him!) Without such rapid, "user friendly" survey techniques, 1) we will never map large areas adequately on a routine basis and 2) experiments that are not specifically "bottom mapping" experiments will be hampered in their analyses due to lack of bottom property information. This might be a 6.1-6.2 transition

issue, but its resolution means a lot to 6.1 research. This also sounds like an area of development where ONR Marine Geology and Geophysics (G&G) participation would be beneficial; G&G contributed heavily to the development of the chirp sonar, and so this would be right in line with their historical interest in developing geological survey tools.

I would also like to see what I will call, for lack of a better phrase, a "better interface" between the poro-elastic ("Biot-Stoll") descriptions of the bottom and the geoacoustic (complex soundspeed, shearspeed, and density) descriptions. It was clear at the workshop that some people were more comfortable with one picture than another, and that the prescription for going from one picture to another was not clear to many participants. Perhaps a good review article in the Journal of the Acoustical Society by one of the more senior people in bottom acoustics would be helpful to the community as regards that issue. Also, it would perhaps be desirable to have software available for translating from one picture to the other.

Water Column Acoustics

While the water column was ignored for many years (to my mind, anyway), the past few years have seen a number of experiments performed addressing water column issues, which has allowed us to make up significant ground. Since 1992, the following experiments have probed shallow water column issues: 1) the 1992 Barents Sea Polar Front experiment (fronts and internal waves), 2) the 1995 SWARM experiment (nonlinear and linear internal waves), 3) the *three* 1996-97 PRIMER experiments (fronts, eddies, internal waves, and fine structure), 4) the 1996 SESAME experiment (fronts, eddies, internal waves), 5) the Intimate '96 experiment (internal waves), and 6) the 1996 Yellow Sea preliminary experiment (internal waves). I've probably missed a few experiments, as well as slightly misstated the goals of some experiments, for

which I offer my apologies. But that list gives you the basic idea that *something* is definitely happening as far as measuring the water column with good acoustics coupled to good, simultaneous oceanography measurements. I would make two comments on the above group of experiments. First, it might be useful for the PI's of all these experiments to gather for a "mini-conference" to compare analysis results and directions. (Note: there is a special session at the PSU ASA meeting in Spring 97 that will address at least the oceanographic part of many of these experiments.) And second, there are still a lot of measurements and issues that the above experiments did not get to that need to be carefully addressed. On my list of desirable *further* items would be: 1) measurements at a lot more frequencies, going in octaves (at minimum) from 25 Hz to 3200 Hz, 2) longer continuous samples of the acoustic transmissions (10-20 minutes) combined with 2-4 weeks of time series overall, 3) good, 360 degree *azimuthal* measurements of scattering from fronts, internal waves, etc. and 4) horizontal and vertical array deployments for coherence studies.

One interesting point to make concerning the water column experiments and modeling of the water column structure is that shallow water acoustics efforts like the ones above have been taking "ancillary" or "supporting" physical oceanographic (PO) data that have actually pushed the state of the art in PO somewhat. I think some acousticians were surprised at the meeting to find out that the PO community did *not* know about the coastal oceanography on all the time and space scales we needed for our work, and that we were breaking some new ground for PO as well. This came about because, historically, coastal PO did not look so hard at the fine space and time scales we need to know about for acoustics purposes; they generally looked at slower, broader features. Moreover, their measurement techniques were previously somewhat limited compared to modern technology. However, with ADCP's, Sea Soar, and other modern technologies, the PO community *can* help us get the measurements we need,

which are also things they need, as they study finer scales in oceanography. (And conversely, we have helped them!)

The second point to make about the PO is that we should try to link strongly to the PO *modeling* efforts in providing oceanographic input to acoustic propagation and scattering codes. The constraints that ocean dynamical equations can provide give us more sensible inputs to the acoustic models; data assimilating ocean models might produce the best input available. However, these models are not yet as fully developed as would desire for acoustics purposes, and again we are pushing the state of the art in PO. In particular, the PO models do not combine the large scale and fine scale oceanography well yet, i.e. the large scale models will handle "kilometer-ish" resolution and subtidal frequencies, but they won't handle the $N_{max}(z)$ buoyancy frequencies and 10's of meters scales needed to handle solitons. Fine scale soliton models (e.g. John Apel's recent "dnoidal" wave model) on the other hand do not relate to subtidal frequency processes. The link needs to be made, in order to aid both acoustics *and* oceanographic efforts. This may be 6.1, 6.2, or even higher research, but whatever the designation, it will be *useful* work.

One more note on water column phenomena, specifically as regards deterministic versus stochastic descriptions. One of the livelier discussions of the workshop addressed whether one should model propagation through solitons deterministically or stochastically. This is not a trivial question. Given the exact bathymetry, water column stratification, tidal forcing, and wind/ thermohaline forcing of the ocean in the region of generation and propagation of solitons, one could *in theory* predict what we would see for a soliton field. *However,* we will never know all this information, so that in reality we will wind up with an estimation of the field. The field we estimate will have the correct properties for solitons, but its parameters will be different from the real ocean field. We are thus

looking at a deterministic process but with unknown parameters, the typical scenario for internal wave work! Perhaps the biggest difference between solitons and linear waves is that we know the generation sites and mechanisms a lot better for solitons, so that these do have some potential for partial predictability. Given this situation, do we use deterministic models, "conditional probabilities" as McCoy has suggested, or fully random approaches, as Tappert has suggested? This issue will be a lively one to address in the near future, not just for solitons, but for eddies, fronts, and other ocean phenomena which have some dynamical structure and order (though they are also turbulent/ chaotic due to the nonlinearities in the Navier-Stokes equations) but whose exact structure we will never be able to know exactly due to limited measurement resources. I think an indication of how interesting this problem will be is seen in the oceanographic data on solitons taken by the many experiments listed above. To my eye, there are significant *differences* as well as similarities in the soliton/ internal tide fields seen by various investigators, indicating that we will *not* be looking at a trivially simple ocean. Even the linear internal wave field in shallow water is unknown at this time; there is an ONR PO initiative called LIWI investigating this field, but there is much work to do here, and results will probably be few years in coming.

All in all, the coastal water column is providing some extremely good research questions to the science community, and the efforts of that community promise to provide both good science results and vital information to the Navy in the next few years.

Modeling

Modeling of acoustic propagation and scattering is a pretty highly evolved art form at this point in time, and Fred Tappert's semi-facetious remark that "it has all been done" is not totally amiss. I think modelers *have* explored many of the physics, 3-D, broadband, etc., issues so that they know pretty much what to do

for most cases of interest. However, in practice, the community of model *users* (as opposed to modelers) who employ codes in day-to-day analysis work *do not* have access to all the types of codes that they need. OALLIB (http://oalib.njit.edu/) which I regard as one of the best things since sliced bread, provides the basic "flavors" of code, i.e. ray, mode and PE, but these are generally (though not totally) 2-D and narrowband. To do broadband calculations, one generally has to resort to Fourier synthesis, and it would be nice if all the codes available had "hooks" for this in place. 3-D is also a serious issue in shallow water, particularly due to topographic steering, and real 3-D codes (as opposed to Nx2D, which of course is still quite useful) are still relatively rare and a bit hard to use. FOR3D (PE), HARPO (ray) and Ching-Sang Chiu's 3-D mode code seem to be the front runners in the area. I would personally suggest that ONR, which already supports OALLIB, go even further with its model support and make sure that a very complete suite of models is available to the U.S. underwater acoustics community.

Another issue in modeling is that one uses very accurate models but very inaccurate ocean and ocean bottom input to make predictions of things like propagation loss, travel times, etc. As the models generally take in deterministic data (i.e. either one realization of a random process or the mean of a range of parameter values), we get out a perfect, deterministic prediction *with no error bars*. This is unrealistic, as we all know. Yet there seems to be precious little effort made to quantify the effects of input error in codes. It is tacitly assumed that the user of a code can iterate the model over the full space of possible input parameters to get such answers, but this is generally neither possible nor convenient. David Rubenstein offered a few references to work on getting error/ predictability estimates from "smart" algorithms, and I think this is a good topic for the community to pursue.

Postscript

Since I don't have anything much to add to the vertical/ horizontal resolution or signal processing discussions, let me stop here. Again, let me state that the opinions I expressed above are my own. I hope they are not all completely off base, and that some might even be useful.

1. THE BOTTOM ACOUSTICS GROUP REPORT

Paul Vidmar, Group Leader

1.1. Introduction

Scattering from the seabed is one of the most challenging and important problems in understanding acoustic propagation in shallow water. Reverberation, time spreading, and angle spreading of acoustic signals are regularly observed in shallow water experiments and are thought to be caused by scattering from the sea floor and subbottom. Our current inability to make reliable predictions of these phenomena emphasizes our lack of knowledge of the physics of scattering and underscores the importance of the scattering component of bottom acoustics research.

While many individual scientific issues related to scattering were raised during the panel discussion and the meetings of the working group, one recurring topic was the lack of knowledge of the features of the subbottom producing scattering. Geoacoustic "ground truth" is currently lacking and is sorely needed to guide theoretical and computational research, facilitate design of successful field experiments, provide the basis for analysis and interpretation of acoustic data, and for eventual application to Navy problems. The working group also identified some issues concerning the basic geoacoustic properties of sediments. Below we summarize discussions of the working group. Following that, we make some recommendations for future research directions and identify the relevance of this work to the Navy.

1.2. Scattering

Although theoretical and computational work has made progress toward understanding individual scattering mechanisms, it is not clear how this work can be applied to the problem of scattering from the seabed in shallow water. One difficulty is the fact that the sea floor topography and subbottom geoacoustic structure have a complicated mixture of length scales, orientations and physical properties. The scattered field is thus inherently three dimensional, highly frequency dependent, and is produced by many mechanisms acting in concert. Another, possibly more serious, difficulty is that there are very few measurements of subbottom variability on scales important to scattering - and almost none in areas where acoustic data were collected. A knowledge of the subbottom features that cause scattering is crucial for providing direction to theoretical and computational research and for making meaningful interpretation of acoustic data possible. While some progress has been made in developing techniques for measuring subbottom properties at scales of interest, notably applications of borehole tomography (Yamamoto, U. of Miami), chirp sonar (Turgut, NRL), and x-ray tomography (Anderson, Texas A&M, and Turgut, NRL) there is still disagreement in the scientific community concerning the interpretation and accuracy of data collected with these approaches. Below, we have organized and summarized these and other scientific issues raised by the working group.

Statistical Characterization of the Environment

The working group identified three different aspects of the sea floor and subbottom variability that need a statistical description because the scale of variability is so short that a deterministic description is not practical. They are: surface roughness, subbottom fluctuations, and reflecting objects. We distinguish between more continuous variations in properties (fluctuations) and reflecting

objects (such as layers, gas bubbles and shells) because the physics of scattering is different and they may require a different statistical characterization. The key to developing a statistical characterization of these features is availability of measurements of their geoacoustic properties.

Surface roughness: The statistical characterization of surface roughness is a fairly mature subject with many data sets available. The power law spectral characterization appears to work well and has been used by several researchers. The remaining issues involve extrapolation in terms of scale and geographic area (See Extrapolation section below). The application of the same techniques applies to characterizing the small scale roughness of subbottom layers.

Subbottom Inhomogeneities: There are very few measurements of subbottom fluctuations. Yamamoto (U of Miami) uses borehole tomography to measure subbottom fluctuations with resolution of about 1 m or less. He processes the data to obtain a two dimensional power spectral representation and has achieved success in applying this characterization to the prediction of backscattering from the sea floor. On a much smaller scale (1 mm resolution), Anderson (Texas A&M) and researchers at NRL use x-ray tomography to measure the three dimensional structure of very small scale fluctuations. Developing an acceptable three dimensional statistical characterization and will require even more data to be collected at various resolutions.

Reflecting objects: Several classes of reflecting objects are currently being studied. Turgut (NRL) uses chirp sonar data to obtain the three dimensional structure of layers in the subbottom. Anderson (Texas A&M) and NRL researchers use x-ray tomography to obtain the characteristics of gas bubbles, shell fragments, etc. found in the upper part of the sea floor. These data may be sufficient to begin developing statistical characterizations of these objects. The

main issues here involve extrapolation and examining additional scattering objects.

Scattering Mechanisms

Working group discussions identified several scattering mechanisms that need additional theoretical, computational, and experimental work. These mechanisms are: Volume inhomogeneities: Although several researchers have made progress, more work is needed to develop theories that are not empirical but driven by measurable environmental parameters. Work by Yamamoto (U of Miami) is proceeding in this direction using his borehole tomography measurements of velocity and density fluctuations as input to his scattering theory.

Finite size layers: Work needs to be done to describe scattering from a single finite size layer, such as a sand lens in a clay sediment, and from an ensemble of such layers. Edge effects, resonances, and multiple scattering may be important aspects of scattering from finite layers. Work by Turgut (NRL) and Badiey (U of Delaware) is making progress toward providing experimentally derived parameters for such layers in shallow water sediments. Shear coupling: While shear wave effects in marine sediments are negligible under most circumstances, it is possible that they have a role in the scattering process. Two factors make this possible: (a) the gradients in volume inhomogeneities may be two orders of magnitude higher than the average gradients in the sediment, leading to significant gradient driven coupling, and (b) shear waves may travel only a short distance to encounter a scatterer and, hence, may not be totally absorbed. Computational work by Stephen (WHOI) is the only work currently addressing this topic.

Orientation relative to the horizontal: Layers, striations on surfaces (sand waves) or elongated inhomogeneities that are oriented at an angle to the horizontal induce an azimuthal dependence to the scattering process. Borehole tomography carried out by Yamamoto (U of Miami) has measured the non-horizontal orientation of volume inhomogeneities and he has included them in his calculations of backscatter. More work is needed to extend this work and to develop an understanding of scattering from other non-horizontal structures.

Single and multiple scattering: Almost all theoretical work deals with scattering in the single scatter approximation. Work needs to be done to deal with multiple scattering and examine the validity of the single scatter assumption.

Theoretical and Computational Directions

The working group felt that theoretical and computational research should include the following aspects of the scattering problem:

Frequency dependence: Research should describe a broadband process to handle the expected strong frequency dependence of scattering.

Coherence: Research should move beyond predicting mean levels and come to grips with the moments of the acoustic field such as coherence (spatial, temporal, frequency, angular).

Azimuthal dependence: The scattering process is expected to be inherently three dimensional and needs to be treated as such. Out-of-plane scatter due to scatterer geometry or orientation needs to be addressed.

1.3. Geoacoustic Ground Truth

While the working group agreed that we needed to know the structure of the subbottom at scales from some fraction of an acoustic wavelength (maybe as

small as 1/10) to the typical size of an experimental region, no agreement was reached on what to measure or how to obtain that characterization. This state-of-the-art is truly astounding, given the critical need for "ground truth" as a basis for theoretical and computational work, design of experiments, and interpretation of data. Many methods for obtaining data about the subbottom were discussed (see list below), but each had its detractors as well as supporters. Clearly, the problem of characterizing the subbottom must be dealt with before any meaningful progress can be made toward understanding the physics of scattering in shallow water environments. In contrast, measuring and describing bathymetry at the required scales is in fairly good shape. There are recognized methods of collecting data (multibeam bathymetry systems, stereo photography, laser line scan systems) and models for characterizing bathymetry (power spectral models).

Some Methods for Measuring Subbottom Variability

- Borehole tomography for fluctuations and layers
- Chirp sonar for layers
- X-ray tomography of cores for high resolution structure
- Seismic profile for large scale features
- Analysis of cores for vertical structure and fields of cores for horizontal structure
- Extracting P wave velocity from S wave measurements taking advantage of the higher resolution of S wave velocity due to smaller wavelength
  - Penetrometer for shear strength, assuming a relationship between shear strength and shear velocity
  - Interface wave inversion
  - Gravity wave inversion

Electromagnetic measurements, assuming a link between electrical and acoustical properties.

1.4. Extrapolation

This topic deals with the often neglected problem of extending measurements outside their initial domain of validity. There are two aspects of the problem, geographic extrapolation and extrapolation of scale. Geographic extrapolation deals with the problem of extending a few localized measurements of sea floor and subbottom structure to characterize an entire region. Extrapolation of scale deals with the problem of using measurements of structure on one scale to predict structure at larger or smaller scales. The key to making progress in these areas is research to link geological processes and stochastic descriptions relevant to acoustics. Once this link is known, geological data and interpretation can be used to develop sampling criteria, establish limits on extrapolation to higher resolution, and provide guidance for interpolation and smoothing. Thus, extrapolation is a combined geology and acoustics problem that needs coordinated interdisciplinary research for progress to be made. The working group identified research issues that apply to extrapolation of both surface roughness and subbottom variability:

Geographic extrapolation:

- How far from a measurement location does a stochastic description of roughness or subbottom variability apply?
- How far apart do stochastic descriptions need to be measured to characterize an area?

Extrapolation of scale:

- How robust are power law spectral distributions? What are the limits in extending distribution to smaller scale features?
- What procedure should be used to interpolate or smooth data for input to models?

1.5. Sediment Geoacoustics

There are still several outstanding research issues involving the geoacoustic properties of shallow water sediments. Most notable is the problem of attenuation. We are still in the situation where estimates of attenuation based on measured physical properties are not reliable and inversion of acoustic data is needed to obtain attenuation values for an area. We do not know what portion of the measured attenuation is due to scattering and what is due to the absorption of energy. There are also questions concerning the importance of velocity dispersion (which must necessarily accompany absorption), the role of small quantities of gas in sediments, and the mechanism for the penetration of low angle energy into the sea floor. Progress on these issues may well require an interdisciplinary approach involving physicists, chemists, geologists, and acousticians to piece together a porous media theory based on an understanding of the acoustics of the micro-structure of sediments. An additional issue raised by the working group is the possibility of the temporal variability of sediment properties in shallow water due to biological activity, storms, and seasonal or daily heating. We do not know the characteristic spatial or temporal scales for these changes as they affect the geoacoustic properties of the sediment or how they affect the statistical characterization of the sea floor or subbottom.

1.6. Issues for Experiment Design

In addition to emphasizing that experiment design should ensure the collection of all data (including sea floor and subbottom data) needed to test the hypotheses of an experiment, the working group identified several specific issues related to bottom interaction that need attention in designing an experiment.

- The goal of an experiment should be to understand acoustical mechanisms (scattering from roughness, from volume inhomogeneities, from layers, from gas bubbles, etc.) rather than

producing a single number (scattering strength) that combines the effects of all mechanisms. Experiments should be designed to isolate mechanisms.

- Experiments should start with simple stochastic environments and move to more complicated environments as our understanding of scattering physics increases.
- Experiments should be located in existing natural laboratories to take advantage of geological and geoacoustic work that has already been done. Additional characterization of sea floor roughness or subbottom variability needed for an acoustic scattering experiment would extend and complement the existing environmental characterizations of the natural laboratories.
- An area characterization methodology needs to be developed to specify the number and location of detailed sea floor roughness and subbottom variability measurements required in an experiment.
- Calibration of sensors (geophones or hydrophones) on or beneath the sea floor is not well understood.
- Tank and laboratory experiments are valuable and should be continued. They provide very controlled conditions (often impossible to achieve in an at-sea experiment) that can examine the physics of individual scattering mechanisms and convincingly validate theoretical predictions.

1.7. Recommendations

The most important issue for bottom acoustics in shallow water is the problem of characterizing the structure of the subbottom on scales needed to describe scattering mechanisms. The working group could come to no consensus about what constitutes ground truth nor could they identify any measurement techniques that were universally accepted as accurate and reliable. This is clearly a fundamental issue that must be dealt with. Without reliable measurements of subbottom variability, theoretical and computational efforts are hindered and it is impossible to unambiguously interpret acoustic data from at-sea experiments. Other important research issues are those dealing with stochastic characterization of subbottom variability, the physics of individual scattering mechanisms,

extrapolation in scale and location, porous media theories based on the micro-physics of sediments, azimuthal and frequency dependence of scattering, and the coherence of the sound field.

1.8. Navy Relevance

Understanding the scattering process and the ability to predict coherence and environmental spreading of acoustic energy has direct application to improving models used to predict the performance of Navy acoustic systems. Developing a technology for measuring subbottom variability and a methodology for extrapolation would find application in the development and maintenance of geoacoustic databases used to provide input to performance prediction models. It is also possible that new signal processing algorithms and system concepts would flow from an understanding of the effect of the sea floor on active and passive acoustic signals.

2. THE WATER COLUMN GROUP REPORT

Michael J. Buckingham, Group Leader

2.1. Introduction

It is a truism to say that the water column plays the central role in underwater acoustics, for it is here that sounds are created, transmitted and received. The boundaries may exert their influence on the spatial, temporal and even spectral properties of the field, but the water column supports its very existence.

Clearly, the question of acoustic propagation through the ocean medium is an important one. However, ocean-acoustic propagation modeling has been the subject of intensive research over the past decade or more, with the result that a number of highly efficient numerical propagation codes now exist that provide an

adequate prediction capability in many circumstances of interest to the underwater acoustics community. This is not to say that the problem of predicting acoustic propagation in the ocean has been entirely solved, since there are still some areas that need attention, notably in connection with environments that support strong 3-dimensional effects. But it is now felt that existing propagation models are sufficiently well developed for emphasis to be placed elsewhere, on areas of ocean-acoustics research that are important to future navy needs.

Two specific topics, both stochastic in nature, are considered to be of immediate interest: acoustic fluctuations induced by various oceanographic processes; and ambient noise, including air entrainment processes and ambient noise inversions to obtain information about the ocean environment. It is recognized that a research program designed to address these issues must be based on four tightly coupled components: a) experimental planning; b) measurements; c) theory; and d) modeling.

2.2. Acoustic Fluctuations In Shallow Water

Internal waves in deep water are reasonably well represented by the Garrett-Munk spectrum (Flatté, 1979), enabling fluctuations in long-range acoustic transmissions to be characterized accurately (Colosi, 1994) . The same cannot be said of internal waves and their effects on acoustic signals in shallow water. There is a clear need to develop a theoretical model or models of internal waves in shallow water, since this is fundamentally important to interpreting acoustic fluctuations in continental shelf and slope regions. In fact, a number of oceanographic fluctuation mechanisms need to be characterized, with a view to identifying their effects on acoustic fields in shallow water, including the following:

- internal waves
- thermal microstructure
- solitons
- variability in surface bubble plumes
- variability associated with the shelf-break front
- seasonal variability in ocean structure
- tidal variability

Stochastic modeling of acoustic fields in a variable shallow water environment is also required. Some inroads have already been made into this problem in a recently published analysis of scintillation in a shallow-water waveguide by Creamer (Creamer, 1996) . This treatment is based on averaged equations for intensities and fluctuations (second- and fourth-order moments), and provides insights into the fundamental physics underlying the fluctuating field. Further theoretical developments are clearly essential if a more complete understanding of the links between oceanographic and acoustic fluctuations is to be achieved. A parallel experimental effort is also required, aimed at investigating the coupling between the oceanographic driving fluctuations and the resultant acoustic fluctuations.

However well the fluctuating environment is understood, it will still only be possible to predict the properties of a transmitted acoustic signal in an average sense, in terms of its second- and higher-order moments. An alternative approach is found in adaptive techniques, such as phase conjugation, that are currently under investigation. In effect, the variability in the acoustic travel path is sampled and backed-out of the received signals, leaving them unaffected by the oceanographic fluctuations. There are some parallels here to active noise and active vibration control systems that have received such close attention over the

past two decades. An interesting aspect of phase-conjugate systems is that when the receiver array is not focused an inversion can be performed to determine the properties of the fluctuating field. Phase-conjugation, used adaptively for eliminating travel-path fluctuations and in an inverse mode for characterizing the stochastic field, is regarded as a very important technique in connection with future shallow-water propagation studies.

Shallow-water tomography is seen as another area of interest, and one which has received little attention compared to its deep-water counterpart. There seems to be a good case for a tomographic experiment designed to provide data on shallow-water acoustic fluctuations in support of the theoretical studies mentioned above.

In summary, the research topics identified in this section are listed below.

- Development of shallow-water internal-wave spectra (theory & experiment)
- Theoretical development of acoustic fluctuations in shallow water
- Experimental investigations of links between oceanographic and acoustic fluctuations in shallow water
- Development of phase conjugation and other adaptive propagation schemes
- Shallow-water tomography

2.3. Ambient Noise

Ambient noise has been of interest to the ocean acoustics community for many years, mainly with a view to reducing its effect on signal-detection capability. Recently, it has come to be recognized that ambient noise itself contains information on the ocean environment, which can be extracted to advantage. It is interesting, however, that the classical Knudsen spectrum of noise due to breaking waves, which has been known for the best part of fifty years, still

has no entirely satisfactory explanation. This is a fundamental problem of ocean physics, which needs to be addressed fairly urgently since it has a bearing on several aspects of ambient noise research, including inversions of the noise to determine ocean processes such as gas fluxes across the air-sea interface.

Wave noise arises from the creation of bubbles just beneath the sea surface. An important feature of the bubble field below a breaking wave is the bubble size distribution, for which there is no satisfactory theoretical model although it is known from measurements that it scales approximately as a^{-n}, where a is bubble radius and $2.5 < n < 6$. Another aspect of the bubble plumes, and one that has received very a little attention, is the bubble creation rate. This is particularly important when passive-acoustic techniques are used for interrogating surface processes, since the signal originates with the newly formed, acoustically active bubbles. That is to say, passive systems respond to the rate of creation, whereas active systems, for instance, upward looking sonars, yield information on the quiescent bubble field. The basic physics of the bubble size distribution and the bubble creation rate are both considered to be very important research issues in support of future ambient noise inversions.

Such inversions include the use of ambient noise to determine gas transfer rates across the air-sea interface, which is relevant to absorption of greenhouse gases by the ocean, which in turn has a bearing on global warming estimates. The noise may also be used to establish the statistical distribution of surface waves; and measurements of noise in the water column can provide information on sea floor parameters and to some extent stratification. All such inversion techniques are relatively new and involve various novel ideas. This raises several questions, including robustness and repeatability of the techniques, and performance limitations. There is a recognized need to examine the new methods of stochastic

signal inversion, with the objective of answering some of these questions and identifying limitations on performance.

A region of accelerating interest is the surf zone. Until very recently, little effort had been directed towards the acoustics of the littoral environment and even now almost everything still needs to be done. Complexity is perhaps the characteristic feature of surf zone processes, in terms of the fluid mechanics, the acoustics, and the coupling between the two. Even the simple question of whether sound propagates out from the breaking region to open water and if so, what is the coupling mechanism, cannot be answered with certainty. The acoustics of the surf zone is identified as a particularly challenging and interesting topic of research, which needs to be addressed systematically, with a view to unraveling the essential physics of the environment. From the experimental point of view, several techniques will be needed to characterize the acoustics and oceanography of the surf zone, including Doppler sonars, upward-looking sonars, and bubble counting and sizing devices (acoustic and optical).

A feature of near-shore ambient noise in temperate and tropical climates is sound from colonies of snapping shrimp. Each pulse is extremely intensive (probably highly non-linear) and very brief, lasting no more than 10^{-5} seconds. The overall noise field from the creatures is impulsive in nature, very non-Gaussian, and originates from a random spatial distribution of sources. The bandwidth of the snapping shrimp sounds is approximately 5 kHz to beyond 100 kHz, spanning the performance range of many active sonars. For such systems, the snapping shrimp may be a cause of serious performance degradation. On the plus side, the shrimp provide a form of acoustic illumination in the water column, which can be used to advantage by the ambient noise imaging systems (Acoustic Daylight) that are currently under development. There is a pressing requirement to

identify the spatial and temporal statistics of snapping shrimp noise fields, since so little is known of their properties.

In summary, the research topics identified in this section are listed below.

- Origin of the breaking-wave noise spectrum
- Develop physics of the bubble size distribution from wave breaking
- Develop physics of the bubble creation rate from wave breaking
- Develop stochastic-field inversion techniques
- Assess performance limitations of stochastic-field inversion techniques
- Establish fundamental coupling between fluid mechanics and acoustics in the surf zone
- Quantify the spatial and temporal distributions of snapping shrimp noise in near-shore locations

2.4. Concluding Remarks

In the above discussions of the current and future status of water column acoustics, the effects of the sea floor have been excluded, although clearly topography and other factors influence shallow-water propagation and ambient noise. But bottom effects are under consideration by another group.

On another issue, the ocean acoustics community has accumulated many high-quality data sets over the years, and it is recommended that, whenever possible, these be used to advantage rather than perform repeat experiments. It is also recommended that existing assets, for instance in the form of a planned research cruise, be exploited to the full by the community to maximize the return on the investment.

3. THE MODELING AND SIGNAL PROCESSING GROUP REPORT

William Siegmann, Group Leader

3.1. Introduction

High-quality modeling and processing tools are essential for fundamental understanding of shallow-water acoustics and for detection and localization problems. The geoacoustic and water-column issues that are relevant for scientific progress and for Navy applications are discussed in previous sections. New capabilities for propagation models and signal processing methods that are required to meet those needs are described here.

3.2. Deterministic Modeling

Much progress has been made in developing and validating deterministic propagation models for shallow water. Minor refinements or small accuracy improvements for these models are not needed. The focus of research should be on incorporating new and relevant physical mechanisms and capabilities. It is not enough to construct and test implementations that require supercomputers to run current problems. The models must be practical and efficient on today's high-end workstations, so that they will have a significant shelf life as computational power continues to increase. The goal is a suite of efficient and benchmarked shallow-water "super-models" which subsume earlier versions and allow easy upgrading.

The primary objective is to incorporate the correct physics, or more precisely the best available understanding of the correct physics for the applications of interest, into the propagation models. Example physical mechanisms in earlier sections range from thermal microstructure to poro-elastic sediments with dispersion and anisotropy. A complete picture of the frequency

dependence of all results is crucial. A related role for the models is to demonstrate the connectivity between micro-mechanical modeling (for example, of highly variable sediments using homogenization techniques) and commonly used effective-media theories.

Another major requirement is fully capable three-dimensional models. The role of 3-D scattering (forward and backward) in shallow water cannot be appraised or treated effectively with existing models. Elastic and poro-elastic sediments need incorporation into 3-D models which are suitable for near-shore and other coastal environments. Broadband 3-D models are considered essential. With advances in physical understanding and computational hardware, the time is ripe for attaining practical 3-D capabilities. No suggestions are made for particular approaches, since each has vigorous advocates; hybrid methods may be the strongest candidates.

Even for the best available propagation models, the sensitivity and predictability pictures are incomplete. For 3-D and other new versions, the levels of field uncertainties need to be specified in terms of environmental uncertainty levels. Another modeling issue which might lead to significantly increased efficiency is the possibility of using impedance conditions at the seabed interface, rather than performing calculations throughout the sediment volume. This entails construction of non-local boundary conditions and useful localized approximations to them, over the range of frequencies and geoacoustic sediment properties.

An unresolved problem is modeling effects of scattering from objects in the ocean volume or the (elastic or poro-elastic) sediment. Previous efforts, emphasizing cases with fluid bottoms, concentrated on acoustic interaction with the object in isolation. The challenge is to treat the fully coupled propagation

problem with objects imbedded in a physically reasonable model of a shallow waveguide.

3.3. Stochastic Modeling

Stochastic propagation modeling is critically important for shallow waveguides with substantial and widespread variabilities that are best treated randomly. Some types of stochastic problems for explaining experimental results or testing theoretical predictions are well suited for Monte Carlo treatment. Available well-refined deterministic models can then be used, providing the simulations are feasible. Other types of stochastic problems are better suited for examination by perturbation, moment, or related methods, particularly when behaviors of higher field moments are required. For these it is not enough to develop approximate moment equations; their validity and practicality must be demonstrated.

A principal objective should be determining field coherences (vertical, horizontal, and temporal) in concert with investigating physical mechanisms described previously; a few examples include interface roughness, sediment heterogeneities, gas bubbles, and microstructure. There are corresponding problems for modal and cross-modal coherences. Examining the intermittency of acoustic signals and correlating them with environmental intermittencies is a related issue. The time spreading of broadband signals also should be specified in terms of environmental variabilities.

Scattering and reverberation are persistent modeling problems that have special significance in shallow waveguides. The importance of a practical capability for treating 3-D scattering cannot be overemphasized. This fundamental problem is linked to several issues in previous sections, where relevant physical mechanisms are detailed. Particular attention should be given to using scattering

models to determine scattering cross sections; to discriminate between absorption, attenuation, and scattering losses; to find interface scattering matrix statistics; to specify surface scattering effects (from bubbles, wakes, ice) on signal statistics; and similarly for volumetric (fish schools, microstructure) and bottom (from layering, roughness, inhomogeneities, gas bubbles, and shells) scattering effects. Characteristics of discrete reverberation arising from both isotropic and anisotropic features should be determined, along with 3-D variability from elastic or poro-elastic sediments. Diffuse reverberation, particularly its coherence, from 3-D roughness and inhomogeneities should be treated.

Models of 3-D shallow-water noise statistics, including both natural and man-made sources, are important for fundamental understanding and applications. The evolution of the noise statistics in shallow waveguides needs determined, along with the noise scintillation index. Another issue is developing stochastic propagation tools and procedures for non-stationary fluctuations, one example of which may be the noise field but environmental volume and surface variabilities may be others.

It is important to emphasize that for any of the problem areas, uncertainties in predicted moments are needed in terms of environmental uncertainty estimates. Whether the stochastic propagation is treated by Monte Carlo simulations or averaged moment equations, this requirement holds for signal processing and applications.

3.4. Signal Processing

Results from modeling efforts not only support experimental analyses and enable new theoretical predictions but also impact directly on signal processing and associated inversion techniques. Matched field processing (MFP) is a shining star from the interactions between modeling and signal processing, although

significant issues remain for its optimal and efficient use in shallow-water applications. Such interactions should be strongly encouraged to continue and to extend in other directions as well, particularly for the prediction of field components and statistics that are relevant for signal processing. The following problem areas are focused on processing techniques for source detections and localizations but also concern inversion methods for oceanic and geoacoustic properties. The fundamental ocean science in these two classes of problems are so intertwined that they are not separated here.

Priorities are to specify the quality of matched field processing results and to increase MFP capabilities. The achievable gain using MFP in shallow waveguides has not yet been definitively determined. Statistics should be developed for inversions obtained by MFP. More research is needed for MFP localizations and inversions using horizontal and volumetric arrays. Effects of source, receiver, and target motion on MFP, including reciprocity, integration time, and Doppler, should be determined. A related problem deserving investigation is the influence of non-uniform currents on MFP. Another area suggested for attention is target effects on active MFP applications.

Other research issues are certain extensions for inversion and localization procedures. Among these are capabilities for broadband, coupled modes, and 3-D. Optimum array geometries for inversions should be determined, and emphasis should be placed on specifying parameter resolutions. Target strength inversion, both in the ocean and the (elastic or poro-elastic) sediment, should be investigated using broadband signals.

Efforts should be directed toward promising processing and inversion techniques. One is the collection of phase space methods that include Wigner distributions and wavelets. Another is the set of phase conjugate methods, in

particular their performance in shallow waveguides and with currents. The robustness of mismatch-tolerant processors should be evaluated.

Additional research areas are considered useful for shallow water applications. Noise statistics for signal processing need to be obtained, and opportunistic noise sources should be exploited. The possible advantages of field scintillation characteristics for detection and localization should be explored. The long-term need is to determine optimal array geometries, frequencies, bandwidths, and sensor speeds for shallow waveguide processing.

3.5. Last Words

For coping with shallow water challenges, modeling and signal processing tools have perforce become sophisticated physically, mathematically, and computationally. They will surely continue to grow even more so. With the many approaches and implementations, it is essential for users to have confidence in the available codes. Since a variety of benchmark types and problems currently exist, developers are urged to use appropriate ones for testing and validating their implementations. There is a need for new benchmarks, in particular for assessing 3-D, stochastic, broadband, elastic/poro-elastic, and scattering models. Developers should make their codes as widely accessible as possible, taking advantage especially of the web and ftp sites. Thorough documentation of the code, test cases, and operational guidelines earn such great user appreciation as to mitigate the developer's unsung hours in preparing them.

Appendix A

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Appendix B

ONR Shallow-Water Acoustics Workshop

Workshop Agenda

Moderator: Jim Lynch

----- Agenda and Topics -----

Tuesday, 1 October 1996 8:00 AM - 5:30 PM

Introduction	**7:55 AM**
Programmatic Overview Talks (15 min each)	**8:00 AM**
ONR Ocean Acoustics Program and Shallow Water Thrust	E. Livingston
ONR 6.3 AEAS Modeling Program	E. Estalote
ARPA Shallow Water Multistatic Active Program	W. Carey
NRL 6.2 Shallow Water Signal Processing	S. Wolf
NRL 6.2 Active Acoustics	R. Love
ONR Active and Passive Signal Processing Programs	N. Harned
Shallow Water Active Detection and Classification	J. Bishop
Tactical Passive-Active Detection and Classification	N. Owsley
ONR Broadband Workshop Report	S. Wolf
General Academic Community Talks (10 min each)	**10:30 AM**
Bottom Acoustics	
1. Active Bottom Loss Database Development	P. Vidmar
2. Matched Field Tomography for Estimation of Geoacoustic Properties in Shallow Water	R. Chapman
3. Ambient Noise Coherence in Shallow Water	M. Buckingham
4. Modal Mapping in a Complex Shallow Water Environment	G. Frisk
5. Reverberation Derived Low Frequency Shallow Water Bottom Scattering Strength Estimates	P. Cable, M. Steele, J. O'Connor
6. Modeling Elastic Wave Propagation Using a Complex Screen Method	Xiao-Bi Xie, Ru-Shan Wu

7.	Time Domain Finite Difference Methods in Shallow Water Acoustics	R. Stephen
8.	Measurements of the Sound Speed and Attenuation Structure within the Seabed and its Effects on the Propagation and Scattering of Low Frequency Acoustics Waves in Shallow Water	T. Yamamoto
9.	In situ Compressional Wave Velocity and Attenuation Measurement Using the Acoustic Lance	R. Wilkins, L. Frazer, S. Fu
Lunch in Cafeteria Atrium		**12:00 Noon**
General Academic Community Talks (10 min each)		**1:00 PM**
Bottom Acoustics - cont'd		
10.	1996 Progress Report for MFP Geoacoustic Tomographic Inversion	A. Tolstoy
11.	Computational Shallow Water Acoustics --Shear Waves and Backscattering	D. Lee, J. Bishop
12.	Forward and Inverse Problems in Shallow Water	M. Collins
13.	Seafloor Characterization within the New Jersey and Northern California STRATAFORM Natural Laboratories: Statistical Analysis from High Resolution Swath Mapping Data	J. Goff
14.	Modal Inverses for Bottom Properties	S. Rajan
15.	Frequency Dependent Sound Transmission in Shallow Water Regions	M. Badiey
16.	Direct and Inverse Acoustic Problems in Shallow Oceans	R. Gilbert
17.	Inversion Techniques for Characterizing a Coupled Mode Acoustic Waveguide	D. Rouseff
General Academic Community Talks (10 min each)		**2:30 PM**
Water Column Acoustics		
18.	Preliminary Acoustic Results from the Intimate 96 Shallow Water Tomography Experiment	E. Coelho, S. Jesus, M. Porter, Y. Stephan
19.	The New Jersey Shallow Water Acoustic Random Media Propagation Experiment – SWARM *(SWARM Group: J. Apel, M. Badiey, J. Berkson, K.P. Bongiovanni, J. Bouthillette, E. Carey, C.S. Chiu, T. Duda, C. Eck, S. Finette, R. Headrick, J. Irish, J. Kemp, J. Lynch, A. Newhall, M. Orr, B. Pasewark, J. Preisig, B. Racine, S. Rosenblad, A. Shaw, D. Taube, D. Tielbuerger, A. Turgut, K. von der Heydt, W. Witzell, S. Wolf)*	SWARM Group

20.	The SESAME Experiments-the Effects of Internal Solitons on Acoustics Propagation at the Malin Shelf	R. Field, C. Mire, H. Chandler, M. Broadhead
21.	Shelfbreak PRIMER-an Integrated Acoustic and Oceanographic Field Study in the Middle Atlantic Bight (*PRIMER GROUP: R.C. Beardsley, K.H. Brink, M.J. Caruso, C.S. Chiu, G.G. Gawarkiewicz, J. F. Lynch, J.H. Miller, R. Pickart, A.R. Robinson, K.B. Smith)*	PRIMER Group
22.	Time-Reversing and Phase-Conjugate Arrays	D. Dowling, S. Khosla
23.	Variability of Acoustic Transmissions in the Strait of Gibraltar	P. Worcester, B. Cornuelle, C. Tiemann, U. Send
24.	Internal Tides and Solitons on the Continental Shelf: the "dnoidal" Wave Solution to the KDV Equation	J. Apel, M. Orr, S. Finette, J. Lynch
25.	Coupled Acoustic Mode Propagation through Continental Shelf Internal Solitary Waves	T. Duda, J. Preisig
26.	Observations of cnoidal Internal Waves and their Effect on Acoustic Propagation in Shallow Water	D. Rubenstein
27.	Fluctuations, Coherence, and Predictability of Long Range Acoustic Propagation in Shallow Water	H. DeFerrari, C. Monjo
28.	Effects of Internal Waves on Sound Pulse Propagation in the Straits of Florida	X. Tang, F. Tappert
29.	Large Acoustic Scintillations in the Straits of Florida	F. Tappert, X. Tang, D. Creamer
30.	Environmental Adaptive Acoustics in Shallow Water: An Acoustic Demonstration of an Acoustic Time Reversal Mirror	W. Kuperman, W. Hodgkiss, H. Song, T. Akal, C. Ferla, D. Jackson
31.	Robustness of a Ray Travel Time Inversion Approach	I-Tai Lu
32.	A Model to Understand the Biological Sonars of Dolphins	P. Moore
33.	Reverberation and Internal Wave Studies	J.X. Zhou

Wednesday, 2 October 1996 8:00 AM - 5:30 PM

General Academic Community Talks (10 min each)	**8:00 AM**
Modeling and Signal Processing	
34. Moderately Broadband Shallow Water Acoustics	J. McCoy
35. Coupled Mode Representations for Propagation in Deterministic and Stochastic Range Dependent Shallow Water	R. Odom, M. Park, V. Peyton, J. Mercer
36. Broadband Model Predictions for Shallow Water Pulse Spreading	J. Preston
37. Shallow Water Propagation Effects and Predictability	W. Siegmann
38. The Effects of Rescattering by Rough Interfaces in Waveguides	D. Berman
39. Three Dimensional Sound Propagation in Shallow Water	S. Glegg, J. Riley
40. Pulse Propagation With And Without Range Dependence	M. Werby, N. Sidorovskaia
41. Seismo-Acoustic Field Statistics in Shallow Water	H. Schmidt
Open Panel Discussions (2.5 hours total)	**9:30 AM**
Bottom Acoustics (Group Leader: Paul Vidmar) *Water Column Acoustics (Group Leader: Michael Buckingham)*	
WORKING LUNCH BREAK	**12:00 Noon**
Open Panel Discussions (2.5 hours total)	**12:30 PM**
Acoustics Modeling and Signal Processing (Group Leader: William Siegmann) *Vertical and Horizontal Integration Issues (Group Leader: Ed Chaika)*	
Working Groups Meet in Parallel on Major Topics (2.5 hours)	**3:00 PM**
Bottom Acoustics (Group Leader: Paul Vidmar) *Water Column Acoustics (Group Leader: Michael Buckingham)* *Acoustics Modeling and Signal Processing (Group Leader: William Siegmann)*	

Thursday, 3 October 1996 8:00 AM - 1200 Noon

Working Groups Meet on Major Topics - cont'd (3 hours)	**8:00 AM**
Reports of Working Groups	**11:00 AM**
Meeting Adjourned EXCEPT FOR GROUP LEADERS	**12:00 Noon**
Group Leaders Combine to Organize Final Report (2 hours)	12:00 Noon

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16. Abstract (Limit: 200 words)

The results of an unclassified workshop on Shallow Water Acoustics, jointly sponsored by ONR and DARPA, are presented. The workshop was held on October 1–3, 1996 at the Naval Research Laboratory, Stennis Space Center, and included 83 participants specializing in ocean acoustics, geology and geophysics, physical oceanography, and other disciplines relevant to shallow water research.

The goal of the workshop was to help determine the current status of and future directions for shallow water acoustics research. The report summarizes the deliberations and recommendations of the workshop, and includes detailed reports from the three working groups (bottom, water column, and modeling and signal processing) as well as from the workshop moderator (Dr. James Lynch, WHOI).

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